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THROUGH-THE-THICKNESS[R] BRAIDED COMPOSITES*
FOR AIRCRAFT APPLICATIONS

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Material and structural specimens of Through-the-Thickness[R] braided textile composites have been tested in a variety of experiments. The results have demonstrated that the preform architecture provides significant payoffs in damage tolerance, delamination resistance, and attachment strength. This paper describes the braiding process, surveys the experimental data base, and illustrates the application of three dimensional braiding in aircraft structures.

INTRODUCTION

Through-the-Thickness[R] braided textiles are a new class of composite material which significantly improve material toughness. The technique produces seamless, thick textiles by continuous intertwining of fibers. Materials made from this type of three-dimensional (3-D) reinforcement provide advantageous structural performance especially suitable for aircraft applications.

The use of composite materials in aircraft structures has become widespread in recent years because of their high strength and stiffness relative to weight. Laminated, two-dimensional (2-D) composites are the current state-of-the-art but can be weakened by delamination caused, for example, by holes, cut-outs, or foreign object damage.

For the same weight of material, Through-the-Thickness[R] braided composites have the following advantages compared to 2-D laminates:

- 20% increase in shear strength,
- 50% increase in shear stiffness,
- 40% improvement in residual compressive strength after impact,
- 50% higher tensile strength near cut-outs, and
- 300% greater rib/skin attachment strength.

Components with features such as stiffeners or cut-outs, thick sections, or structures carrying shear loads, or those which have exposure to debris are applications where these advantages can translate into weight savings.

*Through-the-Thickness[R] is a registered trademark of the Atlantic Research Corporation.

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THROUGH-THE-THICKNESS^{R} BRAIDING

Composite materials with reinforcements oriented in two directions are the state-of-the-art for highly loaded structures such as those found in aircraft applications. These materials are fabricated by lamination of woven fabric plies, lay-up of bias or unidirectional tape, or by filament winding. This construction allows for the individual layers to be oriented so that the stiffness and strength of the reinforcement can be aligned in the direction of the applied loads. While tailored for expected loading conditions, the layered, laminated nature of the construction relies upon a relatively weak bonding agent to transfer the stresses from layer to layer and around cut-outs or where damage has occurred. This construction therefore, is susceptible to delamination and crack propagation.

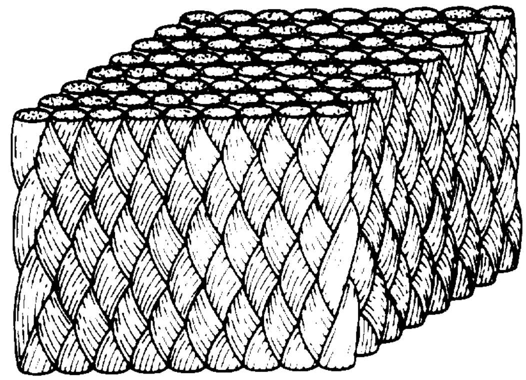
3-D, Through-the-Thickness^{R} braiding was developed by Atlantic Research Corporation to eliminate the possibility of delamination. This is accomplished by continuously intertwining the reinforcing fibers into the seamless, nonlaminated structure[1] shown in Figure 1. The 3-D architecture eliminates planes of delamination with a moderate sacrifice in the in-plane properties. Additionally, the presence of crack-arresting fibers in every orientation markedly reduces the propagation of damage through the structure.

While other 3-D textiles such as multi-ply woven, layer interlock and stitched fabrics also have been developed to prevent interply failure, Through-the-Thickness^{R} braiding is the only textile technique which, by its unique architecture, completely eliminates the delamination prone layered structure. In addition, 3-D braiding eliminates bonding or the use of mechanical fasteners with its unique capability to fabricate complex shapes which totally integrate the reinforcements, for example, between webs and flanges.

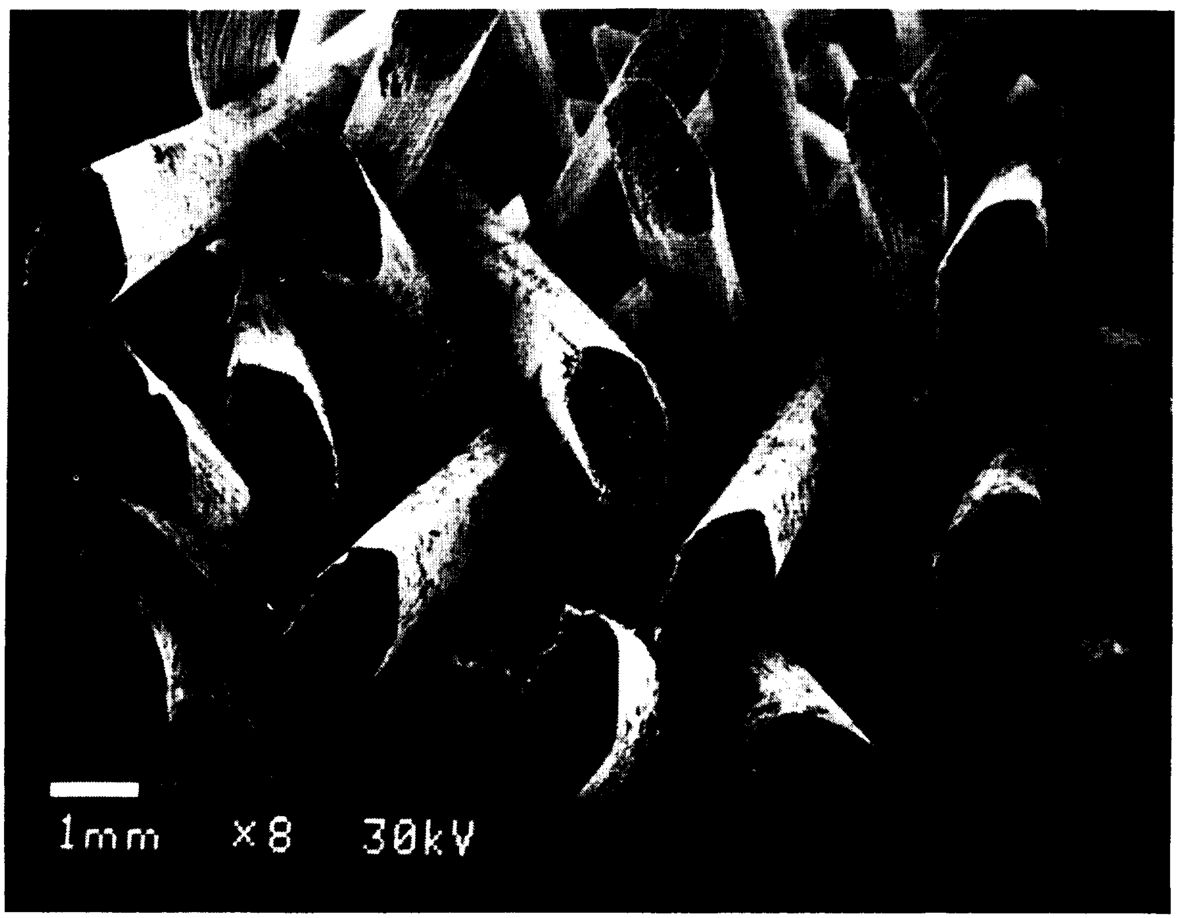
Figure 2 illustrates the operation of an automated 3-D braiding machine. The eight foot diameter machine's scale is apparent from the photograph in Figure 3. The machine has a capacity of 3,168 bobbins, each bobbin holding approximately 30 meters of 12K tow fiber. This braider can produce textile sheets 60 inches in width by 0.25 inches in thickness. It is controlled by an Omron programmable logic controller (PLC) networked with two other 3-D braiders into an MS-DOS based computer. The braiding control software allows input of braid plans, schedules and assigns jobs to individual machines, maintains a quality data history for each job, and diagnoses machine faults.

IMPACT PERFORMANCE

Unintentional impact by foreign objects can weaken composite structures. Runaway debris is a frequent source of damage to the underside of any aircraft and battle damage occurs to military aircraft. 3-D braided composites are extremely tolerant of impact damage.



(a) Intertwined Fibers with No Planes of Lamination.



(b) SEM Photograph of Braided Microstructure.

Figure 1. Through-the-Thickness[R] Braid Structure.

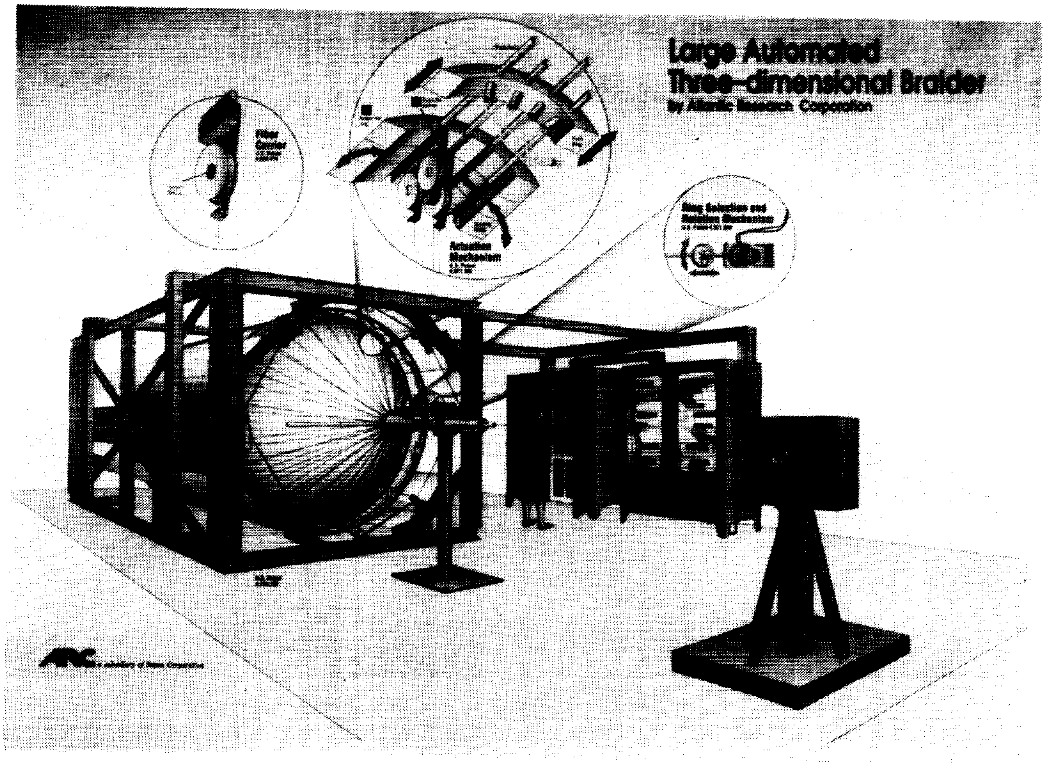


Figure 2

Figure 3

The Naval Air Development Center[2] (NADC) assessed the damage tolerance of 3-D braided composite skins by performing instrumented impact tests of two styles of 3-D braid and a comparison 2-D laminate. The braided skins were fabricated from Celion 12000 carbon fiber with the fibers oriented $(\pm 20)_S$ for style #1 and $(\pm 20/0)_S$ for style #2. [Note: The results of the NADC studies are cited several times in this report. Reference to braid styles #1 and #2 is made to simplify the text and is the notation used by the NADC. This does not imply that ARC manufactures only these two styles of material.]

The braids were impregnated with an aerospace resin, Hercules 3501-6, and autoclave cured. The comparison laminate was manufactured from aerospace grade AS-1/3501-6 prepreg and autoclave cured. The stacking sequence for the 24 ply laminate was $(\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)_S$. The average fiber volume for the three types of material varied between 50% and 55%. Plate specimens 4 inches by 8 inches were tested in an Effects Technology, Inc. ETI-8200 drop tower. Half of each plate was clamped about the edges, leaving a 3-inch square area for impacting and allowing two impact tests per plate.

Four replicate impact tests for each style braid and the comparison laminate were performed at three different impact energy levels: 4 ft-lb (approximate incipient damage), 10 ft-lb (approximate peak load) and 115 ft-lb (through penetration load). Impact energy is plotted versus damaged area in Figure 4. The figure also includes 32 ply AS-6 data from another source[3]. At impact levels above the incipient damage level, the 3-D braids are superior to the laminate in limiting the extent of damage.

The extent of damage directly reduces the strength of 2-D laminates. To verify the expected improvement in post-impact residual strength of 3-D braided composites, several compression after impact experiments were performed at ARC comparing 2-D woven and braided specimens with 3-D braided material. Table 1 describes the specimen construction; both $\pm\theta$ and $0\pm\theta$ architectures were evaluated. Test results are shown in Figure 5. Specimen dimensions were 3 inches square by 0.2 inches thick. Impacts of 150-and 300-inch pounds were delivered by a calibrated, rail guided, free drop penetrator. The impact specimen was held by a 0.5 inch wide clamped edge. At 150-inch pounds surface damage was negligible. All tests were repeated four times.

Because of differences in fiber volume between the test specimens, the results presented in Figure 5 are normalized. Ultimate compressive strengths of undamaged specimens are tabulated in Table 1. Most of the specimens indicated equal drops in compressive strength at 150 inch pounds. However, at 300 inch pounds the 3-D braided specimens still retained that same amount of strength while the 2-D specimens suffered a dramatic reduction in load carrying capability.

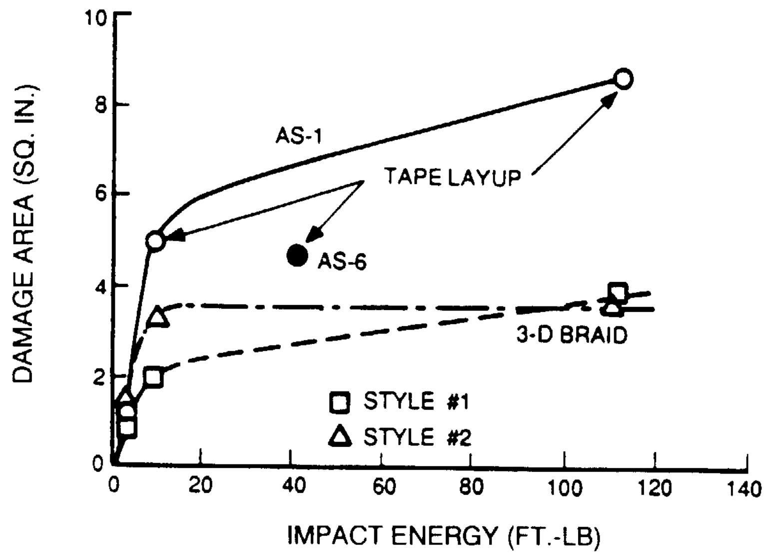


Figure 4. Damage Area Versus Impact Energy.

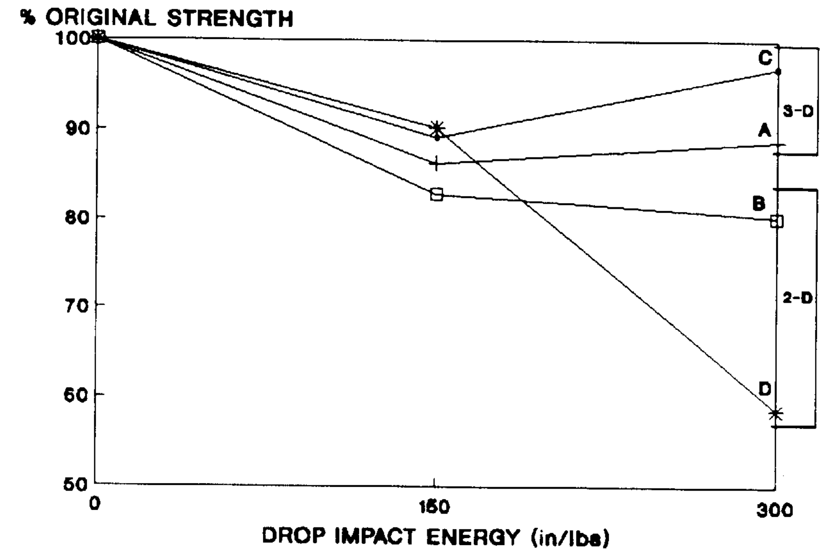


Figure 5. Compressive Strength Versus Impact Energy.

Table 1

MATERIAL DATA FOR COMPRESSION AFTER IMPACT TESTING

Material	Construction	Fiber	Process	Fiber Volume	Ultimate (undamaged) Compressive Strength
A	3-D Braid	AS 4 @ ± 45°	Press mold with Shell 9405 resin	58%	21.7 ksi
B	2-D Weave	AS 4 @ ± 45°	Press mold with Shell 9405 resin	66%	27.5 ksi
C	3-D Braid	G50-300 @ 0° G40-600 @ ± 45°	RTM with Shell 9405 resin	44%	26.1 ksi
D	2-D Braid/ UD Tape	G50-300 UD G40-600 @ ± 45°	RTM with Shell 9405 resin	46%	59.2 ksi

POST-IMPACT FATIGUE

The damage tolerant nature of 3-D braided composites is unaffected by repeated flexure. In studies performed by the NADC, David Taylor Naval Ship Research and Development Center (DTNSR&DC), and Virginia Polytechnic Institute and State University (VPI), the ultimate strength and stiffness of fatigued components were shown to be essentially unchanged from initial values.

Fatigue properties of 3-D braided columns were investigated by NADC[4]. Figure 6 plots percentage of initial buckling and failure strengths for braided Celion 12000/Hercules 3501-6 channel and cruciform sections after one and two million load cycles at 70% of the crippling strength. The figure shows that the ultimate failure strength is virtually unchanged after two million cycles. There is some drop-off of buckling strength but the value remains constant over the fatigue life.

Several experiments have been performed to evaluate the behavior of 3-D braided composites under repeated loading after sustaining impact damage. Performance usually is evaluated in terms of an increase in measured deflection or as a loss of stiffness.

DTNSR&DC[5] conducted fatigue tests on a 3-D braided marine propeller blade. A constant centrifugal load of 2,160 lbs was applied at the center of gravity and a simulated hydrostatic load of 1,650 lbs was applied perpendicular to the center of pressure. The perpendicular load was cycled at a frequency of 5 hertz at an amplitude of 50% of the mean hydrostatic load. At 3.25 million cycles, the blade was impacted at the maximum bending stress location (near the root) with 400 ft-lbs of energy. Local damage was sustained in the form of a crack through the thickness of the blade. On reapplication of cyclic loading, damage did not grow in area during an additional 2.5 million cycles of post impact fatigue. As shown in Figure 7, the strain response remained linear and tip deflections were unchanged.

VPI tested 3-D braids in static and post impact fatigue[6]. The test conditions and results, plotted as normalized stiffness versus normalized life, are given in Figure 8. In order to provide a comparison to an undamaged laminated material, the data from reference 7 was added to the graph. The results show that during the initial 70% of life, the fatigue response of the damaged and undamaged braids are nominally identical, with a slow drop-off in stiffness over time. In contrast, the undamaged laminate exhibits an initial and rapid drop in stiffness followed by a continuous but gradual degradation. Related impact tests also have been reported[8,9,10,11] by others with results consistent with those presented in this paper.

OPEN HOLE TENSION/COMPRESSION TESTING

3-D braided materials are insensitive to the presence of holes in tension and compression stress fields. Aircraft bulkheads typically have holes and other cut-outs to

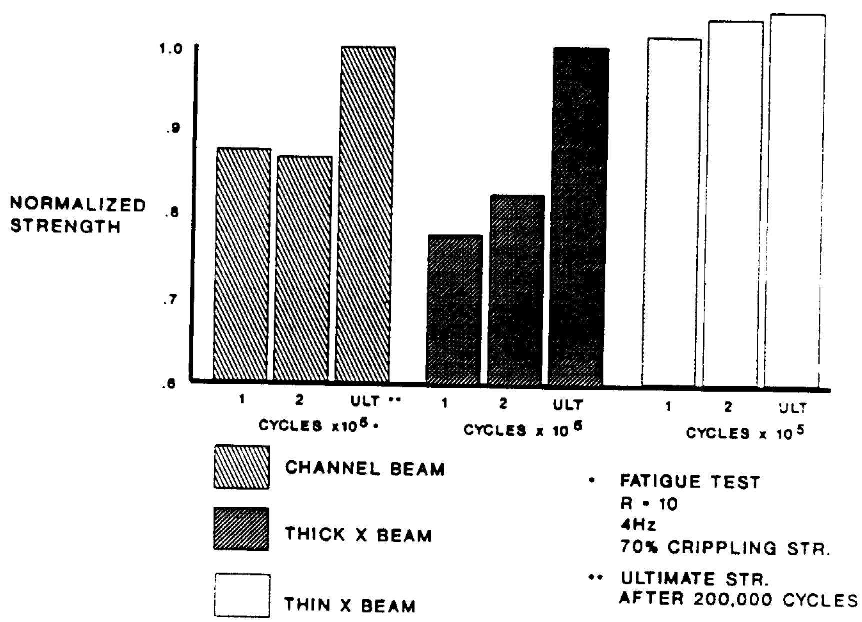


Figure 6. 3-D Braided Column Fatigue.

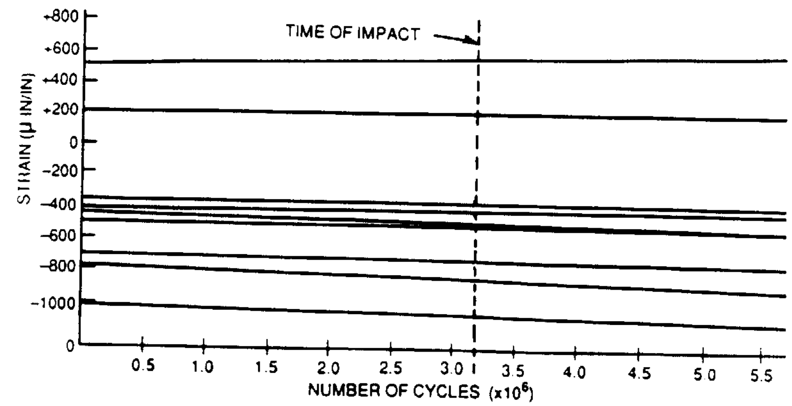


Figure 7. Strain Response of Marine Propeller Fatigued and Damaged.

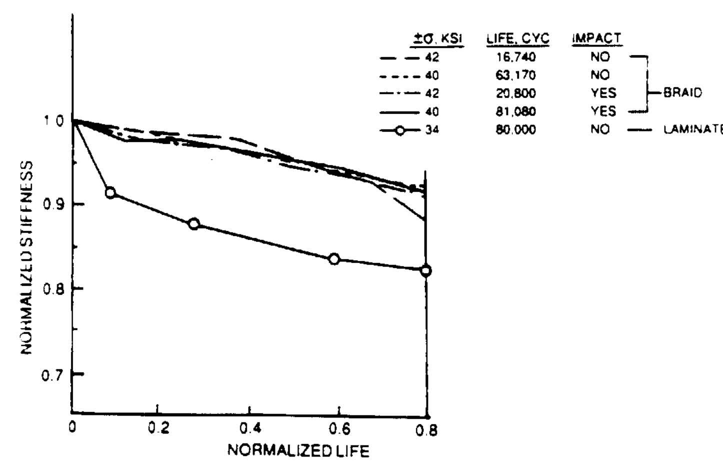


Figure 8. Stiffness Response to Fatigued and Damaged Specimens.

either provide openings for doors, windows, cables and tubing or to reduce weight. The presence of a hole or cut-out results in a local stress riser which magnifies the applied load.

A typical manufacturing approach for laminated composites is to form the hole rather than cut it, because a formed hole reduces the magnification factor[12]. However, such a formed hole increases both design and fabrication costs. In contrast, a hole can be cut or drilled in a 3-D braided composite without additional expense and without magnification of the applied tensile load.

The open hole test is a standard means of determining the material sensitivity to cut-outs. The NADC conducted these tests[2] in tension on the style #1 and #2 braided composites and the laminated composite described previously. The standard tensile specimen was a bar 9 inches long, 1 inch wide and 1/8 inch thick. A 1/4 inch diameter hole was drilled in the center of the bar, reducing the cross-sectional area by one-fourth. Five replicate tests were performed for each material and compared to five tests each of a solid (no hole) coupon.

The average gross tensile stresses (load/no hole area) for each material are plotted in Figure 9. The results show that while the 2-D laminate is initially stronger, it incurs a 50% reduction in tensile strength in the presence of a hole. In contrast, the tensile strength of the style #1 braided material is reduced by less than 1% and by only 13% for style #2. This demonstrates that the 3-D architecture is relatively insensitive to holes and cut-outs of up to one fourth of the load carrying area in a tensile field.

ARC has conducted open hole compression testing on 2-D and 3-D braided architectures described in Table 2. Results are given in Figure 10. Five replicate tests were performed for each material, and test results are normalized to account for fiber volume and orientation differences. Compressive strengths of no hole coupons are reported in Table 2. The results are consistent with those reported by the NADC for tension. The 3-D braided architecture was clearly less sensitive to the presence of a cut hole than the 2-D braid.

STIFFENER PULL-OFF

Stiffness critical members depend on the cross-sectional inertia of built-up sections rather than the modulus of the sections alone. In this case, stiffness depends on the strength of the section connections and on the buckling resistance of the integrated component. 3-D braided skin panels with integral rib or hat stiffeners have significantly stronger skin to stiffener joints than bonded constructions.

A T-beam stiffener pull-off test was conducted by the NADC[13] to determine the failure modes and strengths of integrally braided rib to skin structures. The beam was braided using the style #2 pattern. Figure 11a illustrates the interlocking of the skin

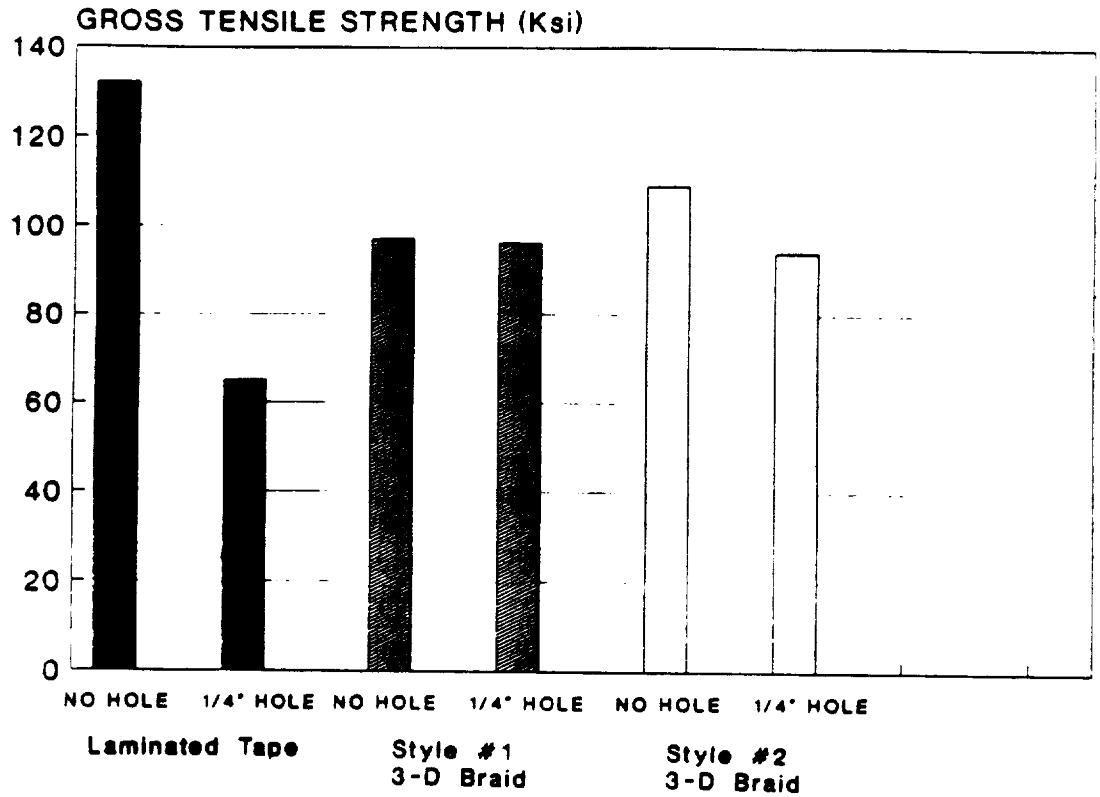


Figure 9. Open Hole Tensile Strength.

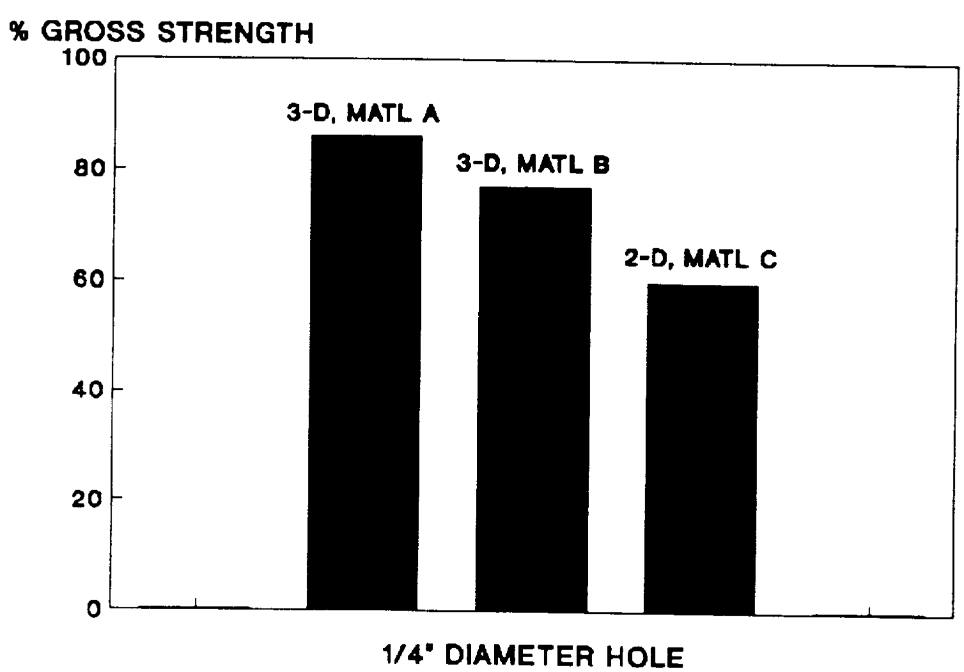
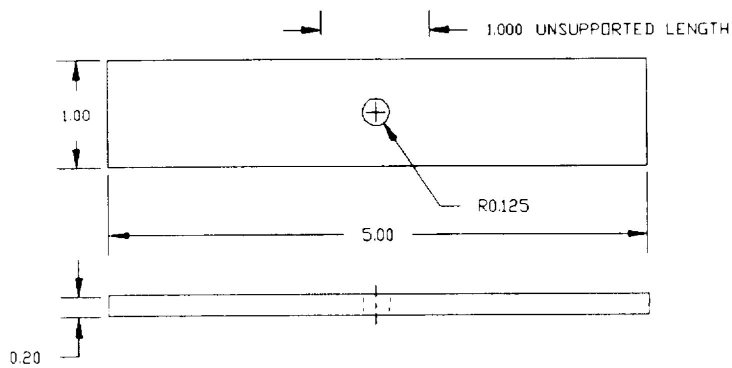


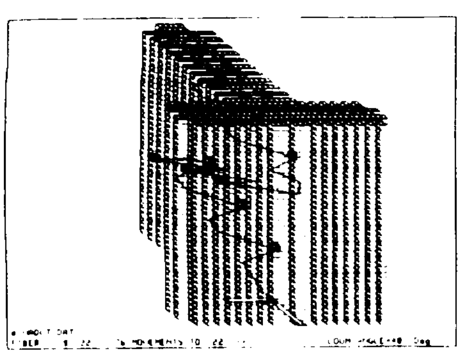
Figure 10. Open Hole Compressive Strength.

Table 2

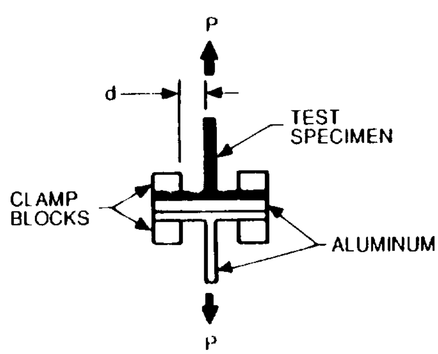
MATERIAL DATA FOR OPEN HOLE COMPRESSION TESTING

Material	Construction	Fiber	Process	Fiber Volume	Ultimate (undrilled) Compressive Strength
A	3-D Braid	650-300 @ 0° 640-600 @ ± 45°	RTM with Shell 9405 resin	44%	20.2 ksi
B	3-D Braid	AS 4 @ 0° AS 4 @ ± 60°	Press mold with Shell 9405 resin	56%	50.8 ksi
C	2-D Braid/ U D Tape	650-300 @ 0° 640-600 @ ± 45°	RTM with Shell 9405 resin	46%	52.3 ksi





(a) Braided Integration of Rib & Skin



(b) Rib Pull-Off Test Set Up

RESULTS

LOAD (lbs)	LINEAR LOAD (lbs/in)	FAILURE MODE
373	447	STIFFENER
325	410	MIXED
190	170	SKIN

AVERAGE LINEAR LOAD FOR BONDED STIFFENER = 50 lbs/in

Figure 11. Stiffener Pull-Off Test.

and rib sections by tracing the path of a single fiber as it travels between them. All of the fibers are traveling in similar paths, resulting in a completely integrated structure.

The test set-up and results are illustrated in Figure 11b. Five tests of the T-beam were conducted with two of the tests using the same clamp spacing on the web. The rib was pulled in tension at a constant head speed of 0.05 inches per second. Because of higher rib attachment strengths, the initial tests resulted in transverse failure of the rib rather than the attachment. The clamp spacing was subsequently varied in an attempt to shift the failure location to the rib/skin intersection. No actual separation was achieved. Instead the failure site and mode were moved to a skin bending failure. Depending on the failure mode chosen, rib tension or skin bending, the load carried per running inch (distance between clamps) varied from 170 lbs/inch to 447 lbs/inch.

Lockheed[14] measured pull-off loads for a similar thickness but bonded T-beam of only 50.0 pounds per linear inch, with failure always occurring at the rib to skin bond. Comparison with the minimum linear load carrying capability of 170 lbs/inch obtained by NADC yields over a 300% improvement in stiffener attachment strength.

MECHANICAL PROPERTIES

Material tests have been performed by Atlantic Research to characterize the strength and stiffness of 3-D braided composites using a variety of graphite fibers and epoxy resins. Some panels were braided to a $(\pm 45)_S$ fiber orientation. Test specimens were cut to yield (0/90) on-axis and $(\pm 45)_S$ off-axis properties. Other panels were braided with a quasi-isotropic orientation of $(0 \pm 60)_S$. Five replicate tests were performed for each material in each loading condition. Tests were performed in tension and compression, on and off-axis, and in shear using the IOSIPESCU test configuration. The average properties for each material are reported in Table 3.

COMPONENT DEMONSTRATIONS

Four structural components have been fabricated in sizes and shapes which go beyond the simple requirements of material testing coupons. These structures, Figures 12-15 illustrate stiffener to skin integration and forming of complex geometries. The structures also demonstrate a variety of processing methods.

The hat stiffened panel, Figure 12, was made from an ARC supplied preform by the NADC using a hot melt/autoclaving process with Hercules 3501-6 resin. The spar, Figure 13, was drape molded and vacuum bag cured at ARC using Shell 9405 resin. The J-stiffened panel, Figure 14, was fabricated in a joint IRAD project with Rockwell NAA. The panel was resin transfer molded using Shell 9405 resin. Figure 15 illustrates a 9 inch by 48 inch sine wave spar braided for Boeing Military Aircraft using Amoco T-650-42 graphite fiber and Radel X comingled thermoplastic. The photograph was taken after initial consolidation processing.

TABLE 3
REPRESENTATIVE 3-D BRAIDED COMPOSITE MECHANICAL PROPERTIES

ORIENTATION	LOADING CONDITION	PROPERTY	FIBER G-40	RTM* T-650	UHM	PRESS MOLD** AS-4
0/90°	Tension	E_X msi	9.2	7.5	14.2	
		S_X ksi	70.2	59.7	70.3	
	Compression	E_X msi	7.2	7.3	11.8	
		S_X msi	35.0	35.1	32.4	
	Shear	G_{XY} msi	0.6	1.1	0.4	
		S_{XY} ksi	9.0	13.1	12.4	
±45°	Tension	E_X msi	3.1	2.4	2.6	
		S_X ksi	35.8	21.5	11.5	
	Compression	E_X msi	3.7	1.3	1.4	
		S_X msi	21.1	20.2	17.4	
0±60°	Tension	E_X msi				6.4
		E_X msi				5.2
		S_X ksi				58.4
		S_Y ksi				35.0
	Compression	E_X msi				5.7
		E_Y msi				5.2
		S_X ksi				50.8
		S_Y ksi				27.0
	Shear	G_{XY} msi				2.0
		S_{XY} ksi				23.1
	Poisson's Ratio	ϑ_{XY}				0.33
		ϑ_{YX}				0.30

* Average fiber volume of 48% using DOW TACTIX 123/H91 epoxy resin.
**Average fiber volume of 56% using Shell 9405/9470 epoxy resin.

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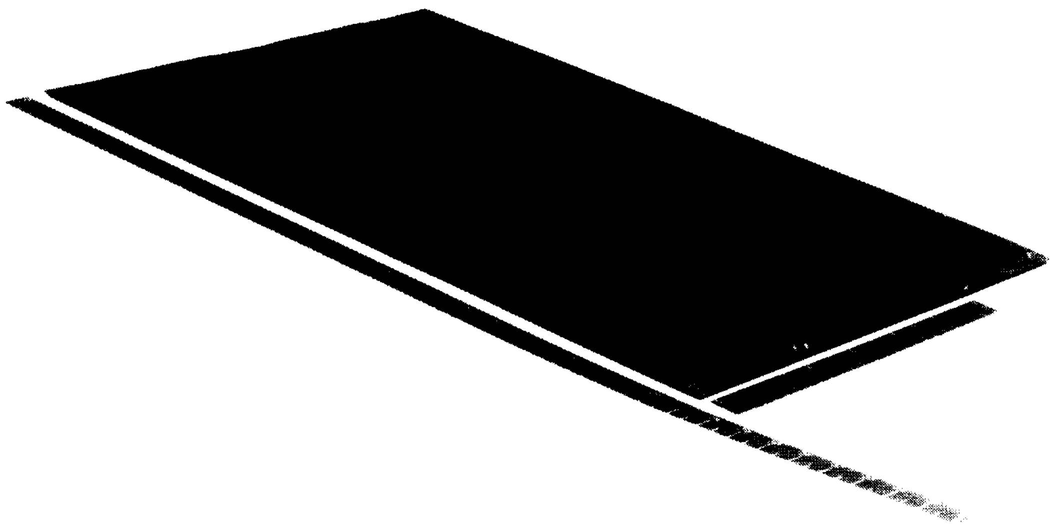

Figure 12

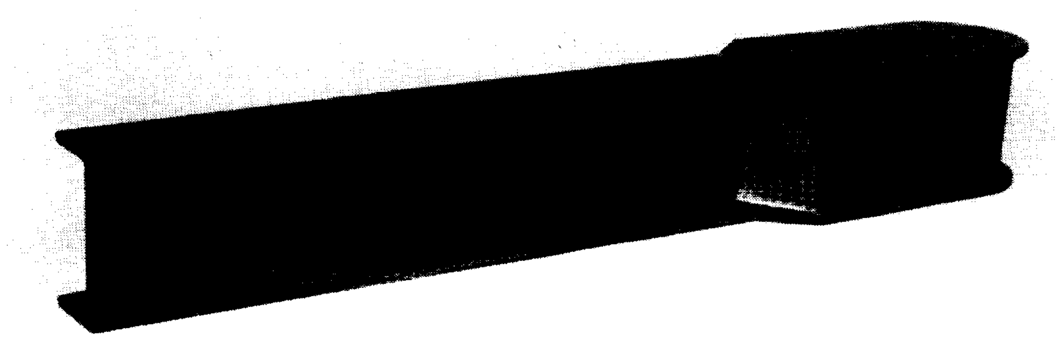

Figure 13

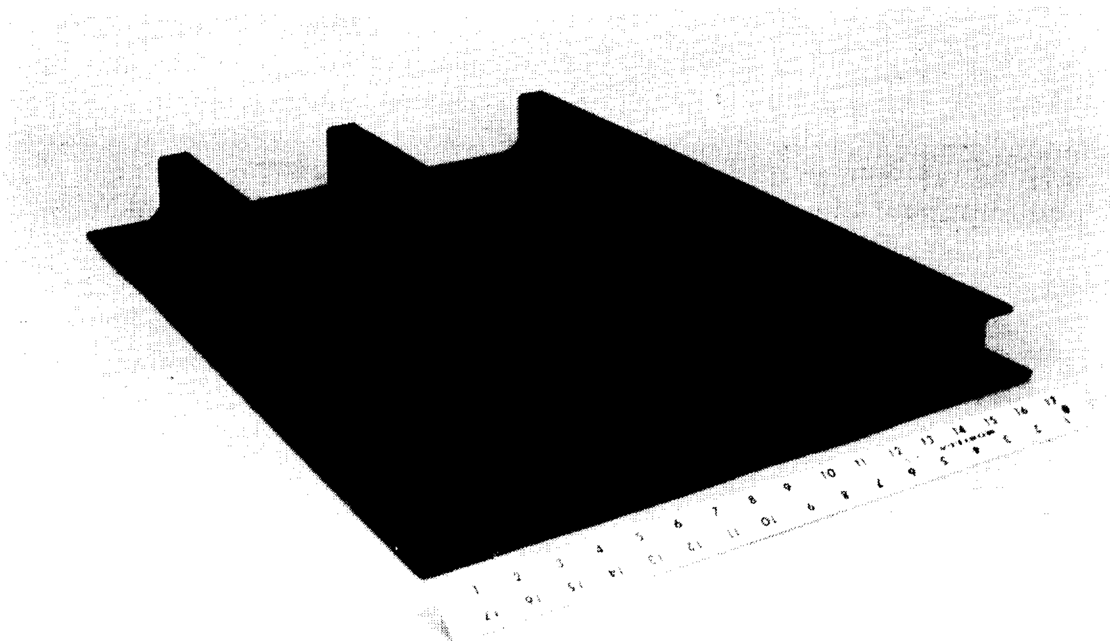

Figure 14

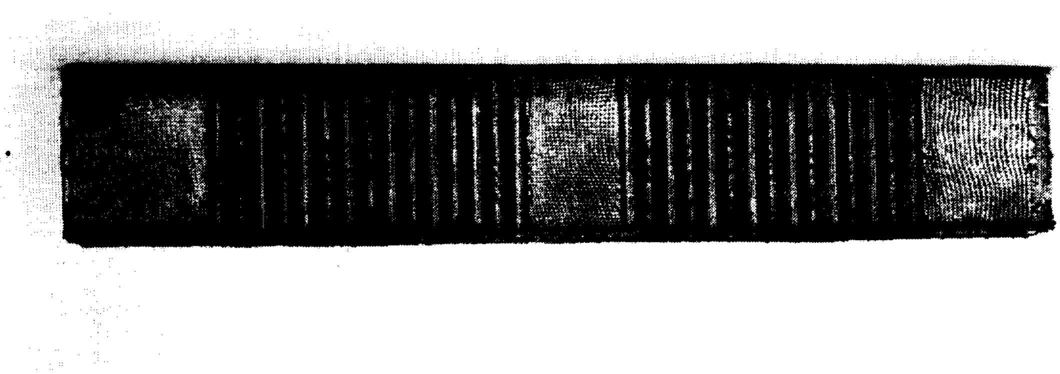

Figure 15

CONCLUSIONS

This paper describes the performance of 3-D braided composites with respect to aircraft structural requirements. ARC's 3-D material possesses a high tolerance to impact damage. Compared to laminated composites, the damaged area is 52% lower for the same impact energy. In addition, the compressive strength is not appreciably reduced in the presence of damage whereas the compressive strength of a lamination is reduced by 40% of its original value. Reduced sensitivity to structural discontinuities, such as holes or cut-outs, is shown by the results of comparative open hole tension and compression tests. The load carrying capability of laminates was reduced by up to 50% while the 3-D braided composites exhibited little strength reduction. Finally, rib stiffeners integrally braided to a skin, demonstrated three-to eight-times the pull-off strength of bonded ribs.

Application of 3-D braided composites to aircraft structures should be guided by the same principles used in the selection of any material system. The material selection must be tailored to the structural requirements consistent with the advantages and disadvantages of the material under consideration. In some cases, notably the compressive strength of undamaged specimens, 3-D braided composites do not provide the same level of performance as laminates. This is because the gain in shear strength comes at the expense of axial performance.

It follows that the best areas for the application of 3-D braids are those components and locations where resistance to foreign object damage, insensitivity to cut-outs, or superior shear strength are required. In these areas, slightly lower initial tensile and compressive strengths are compensated for by the residual strength of the 3-D architecture.

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